PICSC FINAL REPORT

1. Administrative

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2. Public Summary

Climate change is expected to alter the seasonal and annual patterns of rainfall and temperature in the Hawaiian Islands. Land managers and other responsible agencies will need to know how plant species' habitats will change over the next hundred years in order to manage these resources effectively. This is a major concern for resource managers at Hawai`i Volcanoes National Park (HAVO) where current managed Special Ecological Areas (SEAs) for important plant species and communities may no longer provide suitable habitat in the future as climate changes. Expanding invasive species' distributions under future climate conditions also may pose a threat to areas where native plants currently predominate.

The objective of this project is to combine recent climate modeling over the state of Hawaii with existing models of plant species distribution to forecast suitable habitat range under future climate conditions. Projected species range maps were generated for four snapshots in time that coincide with management cycles (2000, 2040, 2070 and 2090) and for three different trajectories of climate change (slow, moderate, rapid) between the present and future. We produced and mapped suitable habitat for thirty-nine plant species, both native and alien, identified as being of interest to HAVO resource managers.

Most of the HAVO SEAs were projected to lose a majority of the modeled native species and all but one alien species; this trend occurred in most SEAs including those at low, middle and high elevations. There was good congruence in the current distribution of species richness and SEA configuration; however, over time the projected species-rich hotspots increasingly occurred outside of current SEA boundaries. Our forecasted shifts in suitable habitat for native plant species will assist park managers in assessing configuration of and prioritizing future work in SEAs. Potential changes to SEAs could include altering boundaries of existing SEAs, establishing new ones, or expanding existing SEAs to incorporate future diversity hotspots in areas not currently managed by park staff. Moreover, our results will assist HAVO managers working with adjoining land owners and partner agencies to prioritize conservation efforts island-wide.

A direct application of our projections is that they can be used to identify locations where major changes in habitat conditions are predicted and where plants are projected to respond to future conditions. Areas with high species turnover occur where climate change signal is strongest, indicative of areas projected to experience greatest climate change. Obtaining additional environmental data in these areas, for example deploying weather stations, will help managers understand what trajectory and extent climate change is occurring, while vegetation monitoring will provide information on how plants are responding to these measured changing conditions. Assisted colonization, the translocation of organisms outside their historically documented range in anticipation of more suitable future conditions, may be a conservation option for consideration.

In Hawaiian culture, natural resources including the land, forests, ocean, plants, animals and inanimate objects were integral to all aspects of life. The Hawaiian cultural renaissance has increased traditional practices including plant collecting. If Hawaiian cultural practitioners continue collecting plants, suitable collection sites may have to move to track shifts in plant ranges due to climate change.

3. Technical Summary

We computed species range by combining current (Giambelluca et al. 2013, 2014) and future (Zhang et al. 2012) climate conditions with species occurrence records from the Price et al. (2012) species range models for thirty-nine plant species, 29 native and 10 alien, identified as being of interest to HAVO resource managers. Modeling the ranges for these species was conducted statewide, and then focused in on their ranges relative to the HAVO SEAs. Price et al. (2012) developed geographic range models for 1,100 Hawaiian plant species based on climate envelopes defined by the minimum and maximum values of climate boundaries (i.e., physiological thresholds) around species occurrences. Price et al. used elevation as a surrogate for mean annual temperature and a moisture zone index as a surrogate for plant available moisture. These models use current and historical occurrence records to describe the current (ca. year 2000) geographic range of each species in terms of environmental and climate factors. We associated the environmental factors (volcano boundaries, elevation, upland area, and young lava flows) in the Price et al. models with both current and future projected rainfall and temperature values to model current and projected species' ranges. We obtained current rainfall and temperature data from the Rainfall Atlas and Climate of Hawai`i (Giambelluca et al. 2013, 2014). This data set represents the current temperature and rainfall in Hawai`i using a thirty-year climatological averaging period from 1978 to 2007. For future projected values, we used the projected changes in rainfall and temperature variables based on the difference between end-of-century (2080-2099) and current (1990-2009) dynamically downscaled climate models from the Hawaii Regional Climate Model (HRCM; Zhang et al. 2012). The HRCM relies on the Coupled Model Intercomparison Project phase 3 (CMIP3) global circulation model (GCM) and the A1B emission scenario (which assumes balanced use across all energy sources) from the Special Report on Emissions Scenarios (SRES); a single forcing of greenhouse gasses and anthropogenic factors in the GCM. This approach allowed us to project the geographic ranges of plant species for the year 2090 using this specific climate change scenario.

4. Purpose and Objectives

Changing global climate conditions, including but not limited to increased global temperatures, changing circulation and precipitation patterns, increased ocean acidification, and sea-level rise are unequivocally linked to human activities (IPCC 2014). These changing conditions result in changes to physical, biological and human-managed systems. Changes in climate conditions will drive changes in biotic systems and species distribution, resulting in changes to the composition of plant communities (Price et al. 2012). These changes can have direct negative impacts on some species by making conditions less favorable for their persistence. A recent study by Fortini et al. (2013) examining climate-based species distribution shifts in the context of habitat area, quality, and distribution illustrated that many native

Hawaiian plants may be particularly vulnerable to climate change. Results from that assessment indicate major range changes for much of the Hawaiian flora due to climate change.

One important consequence of these projected climate change impacts is that native species targeted for protection may have their range shift outside of currently prioritized conservation areas, which can decrease the effectiveness of conservation efforts. Future changes in temperature or available moisture may render current habitat unsuitable for a species; conversely, climate changes may expand the potential range of species towards areas with currently unfavorable climates. Simultaneously, climatic change may allow non-native invasive species to spread into areas where they do not exist today. Indeed, invasive species which generally have greater growth, fecundity and dispersal rates may respond faster to changes in temperature and moisture than established native species.

As a result of climate change, resource managers at HAVO have considered the need to adjust or move their current focal conservation areas to ensure that important species and plant communities continue to be protected over time. Current vegetation management within HAVO is focused on SEAs, which are roughly configured to protect representative plant communities and important species by controlling the most invasive incipient plant and animal species (Loh et al. 2014). Climate change and concomitant shifting habitat distribution may cause mismatches in the communities and species currently protected within SEAs. Park managers therefore want to know if the current configuration of SEAs will continue to provide protection for plant communities and species of concern in the future.

5. Organization and Approach

We modeled the statewide range of 39 plant species identified as influential in the development of management strategies for ecologically sensitive areas such as the HAVO SEAs (Table 1). Based on the HRCM, we interpolated projected temperature and rainfall for four points in time that coincide with management cycles (beginning-of-century [2000], 2040, 2070 and end-of-century [2090]) following three potential climatic trajectories (linear, gradual and rapid) between present and future. We then used the species climate envelope approach by Price et al. (2012) to project the range of each of our target species for each time interval and trajectory (for a total of eight range projections: 2000, 2090 and three each at 2040 and 2070). We modeled changes in plant species range (both contraction and expansion) based on physiological thresholds of suitable habitat as a function of climate change. For each island we clipped the downscaled rainfall and temperature projections and baseline data to the coastline plus a narrow buffer of ocean.

5.1. Aligning Spatial Reference

To enable raster operations, we resampled and aligned all covariate grids (see below) to match the cell size and layout of the online Rainfall Atlas and Climate of Hawai`i, which had a cell size of 0.00225 decimal degrees (approximately 250 m) and used the World Geodetic System (WGS) of 1984 as the spatial reference. The HCRM files for all islands had an initial grid cell size of 3 km, with the exception of Maui which had higher resolution data of 1 km cells.

5.2. Species Envelope Models

We obtained plant species threshold values from Price et al. (2012) for five physical and climate covariate grids: volcano boundaries, young substrate suitable for pioneering plant species, elevation, temperature, and moisture zone. The first model covariate describes 17 different bioregions covering seven of the main Hawaiian Islands: Kaua`i, O`ahu, Moloka`i, Lāna`i, Kaho`olawe, Maui, and Hawai`i Island. Three islands (Kaua`i, Lāna`i and Kaho`olawe) were composed of a single volcano or bioregion, three (O`ahu, Moloka`i and Maui) contained two adjacent volcanoes, and one (Hawai`i Island) formed from five distinct volcanoes. Due to its size and diversity, Price et al. (2012) further subdivided Mauna Loa volcano on the island of Hawai`i into four regions which enabled them to confine historical plant records more precisely within these subregions. Since many plants in Hawai`i evolved in isolation, have limited geographic distributions, and cannot easily move between or adapt to different islands, volcanoes, or regions, the species models of Price et al. (2012) used these 17 bioregions as a means of restricting the projected species range based on documented historic occurrences for each species. The second physical covariate is a binary indicator depicting the presence or absence of young lava substrates which are being colonized by early seral (pioneer) vegetation.

Table 1. List of 39 plant species identified as influential in the development of Hawai`i Volcanoes National Park management strategies for ecologically sensitive Special Ecological Areas.

Scientific Name	Hawaiian/Common Name
Native species	
Acacia koa	Koa
Alyxia stellata	Maile
Cheirodendron trigynum	ʻŌlapa
Cibotium spp.	Hāpuʻu
Coprosma ernodioides	Kūkaenēnē
Coprosma montana	Mountain Pilo
Coprosma spp.	Pilo
Dicranopteris linearis	Uluhe
Diospyros sandwicensis	Lama
Dodonaea viscosa	ʻAʻaliʻi
Freycinetia arborea	ʻIeʻie
Ilex anomala	Kāwaʻu
Leptecophylla tameiameiae	Pukiawe
Metrosideros polymorpha	ʻŌhiʻa lehua
Myoporum sandwicense	Naio
Myrsine lessertiana	Kōlea lau nui
Nestegis sandwicensis	Olopua
Osteomeles anthyllidifolia	ʻUlei
Pandanus tectorius	Hala
Pipturus albidus	Māmaki
Pisonia spp.	Pāpala kēpau
Psychotria hawaiiensis	Kōpiko ʻula
Psydrax odorata	Alaheʻe
Rubus hawaiiensis	ʻĀkala
Sadleria cyatheoides	ʻAmaʻu
Santalum spp.	ʻIliahi
Sophora chrysophylla	Māmane
Vaccinium calycinum	ʻŌhelo kau lāʻau
Vaccinium reticulatum	ʻŌhelo
Alien species	
Clidemia hirta	Koster's Curse
Falcataria mollucana	Albizia
Hedychium gardnerianum	Kahili Ginger
Lantana camara	Lantana
Miconia calvescens	Miconia
Morella faya	Faya Tree
Passiflora tarminiana	Banana Poka
Psidium cattleianum	Strawberry Guava
Rubus ellipticus	Himalayan Raspberry
Schinus terebinthifolius	Christmas Berry

The third physical covariate is a digital elevation model (DEM) that serves as the basis for deriving threshold temperatures, which then goes directly into the species range models to restrict suitable habitat. Our models incorporated temperature in two different ways. First we used temperature as a means of differentiating between upland and lowland areas which are climatologically distinct. The Price et al. (2012) model used the 1,250-m elevation contour as the cutoff between upland and lowland primarily to differentiate dry areas. A critical component of the original Price et al. species envelope models was the inclusion of a moisture zone grid that defined seven levels of moisture availability across the main Hawaiian Islands as a function of rainfall and elevation. The landscape was classified into seven categories: arid, very dry, moderately dry, seasonal mesic, moist mesic, moderately wet, and very wet. We extended the Price et al. moisture zones to the highest upland elevations and to the new, higher maximum rainfalls projected by the climate models.

5.3. Climate Data

The dynamically downscaled climate projections of Zhang et al. (2012) are published in the NetCDF file format, with predicted rainfall and temperature in five-minute intervals for each cell in the 3-km (1-km on Maui Island) grid. We began with monthly summaries (Fortini et al. 2013) of rainfall and minimum and maximum temperature covering the present (1990-2009) and end-of-century (2080-2099) time periods. We then produced annual rainfall values by summing the monthly rainfall by year, and annual temperatures by splitting the difference between monthly minimum and maximum temperature and then taking the mean of that value across all months within each year. To calculate future rainfall and temperature from the downscaled model we employed a procedure that in climate modeling is called the “delta method” (Snover et al. 2013). This technique accounts for model bias by subtracting modeled present conditions from modeled future conditions (creating the “delta”) and adding this value to observed present conditions. In our case we used the Giambelluca et al. (2013, 2014) meteorological atlas for present conditions. The deltas (on a 3-km or 1-km grid) were then down-sampled via bilinear regression to a 250-m grid matching the present-day meteorological data.

5.4 Interpolating Change

We computed the results of climate change statewide and at a decadal interval; however, we focused primarily on the results of interest to HAVO managers at three particular points in the future: 2040, 2070 and 2090, as well as the present. It is unknown how climate change will progress over the century. Therefore, at the two intermediate points we examined three possible trajectories of change: rapid, linear, and gradual, though all three converge at the same point in 2090. We calculated linear change as a straight-line interpolation between 2000 and 2090. For the upper trajectory we assumed a scenario where half the total change occurs linearly in the first quarter of the time span, then again linearly for the rest of the change across the remainder of the period. For the gradual change scenario the change points were reversed; only half the change occurred three-quarters of the way from 2000 to 2090, and the remainder occurred afterwards.

5.5 Estimating Uncertainty

The Zhang et al. (2012) dynamic downscaling does not report explicit uncertainties in its projection of future climate, but we have attempted to approximate its uncertainty by incorporating the variability of its modeled weather. We estimated the uncertainty of that point estimate by calculating a delta of annual precipitation and temperature by subtracting modeled present conditions from modeled future conditions, yielding a total of 400 (20 years present by 20 years end-of-century) deltas. We then used each of these 400 projected climates to estimate the potential range of each plant species. For each pixel on the landscape, we took the proportion of climates where the pixel was suitable habitat as a measure of the likelihood (ranging from 0% = never, to 100% = always) that a location on the landscape would be suitable habitat in the future. We used an 80% threshold to produce maps of species ranges; a pixel was considered within the species range if it had an 80% or higher pseudo-probability of being suitable habitat – meaning that it was suitable in at least 320 of the 400 different interpolations.

5.6. Species change and SEA Evaluation

We quantified the net percent change in species range, and the amounts of contraction and expansion, as minimal, moderate or substantial. We set minimal contraction/expansion at ≤ 20% change, moderate contraction/expansion between 20 and 50% change, and substantial contraction/expansion at > 50%

change, based on the middle (linear) trajectory of climate change. We evaluated each SEA by assessing the change in species richness of the selected set of species between the current (2000) and end-of-century (2090) projections. We considered SEAs that maintained or increased in native richness as optimally situated for future conditions, whereas SEAs that lost half or more of their current native species richness may benefit from additional investigation.

6. Project Results

6.1. State, island and HAVO-wide patterns

In general, most species were projected to contract at lower elevations and the periphery of their range, while any expansions were projected to occur at upper elevations around the volcano summits. Across the main Hawaiian Islands all but three native species — *Dodonaea viscosa*, *Myoporum sandwicense* and *Santalum* spp. — were projected to have a net loss in species range, contracting either moderately or substantially. These three species projected to expand did so only minimally. This pattern of net loss in native species range was projected for all of the main Hawaiian Islands below 1,600 m elevation and for Maui at all elevations. On Hawai`i Island five additional native species were forecast to have a net increase in suitable habitat: *Diospyros sandwichensis*, *Nestegis sandwicensis*, *Osteomeles anthyllidifolia*, *Pandanus tectorius* and *Psydrax odorata*. With the exception of *Diospyros sandwichensis*, which was expected to expand moderately, these species were projected to expand minimally.

Within HAVO, the net percent change in suitable habitat over the century was projected to increase for 11 of the 29 native species, including *Alyxia stellata*, *Coprosma montana*, *Diospyros sandwicensis*, *Dodonaea viscosa*, *Metrosideros polymorpha*, *Myoporum sandwicense*, *Nestegis sandwicensis*, *Osteomeles anthyllidifolia*, *Pandanus tectorius*, *Psydrax odorata* and *Santalum* spp. Our models projected minimal to moderate range expansion for 10 of these species while *Diospyros sandwicensis* was expected to increase substantially. In contrast, eight native species within HAVO were expected to contract minimally to moderately, while 10 species showed substantial contraction.

Statewide patterns for the 10 alien plant species revealed that all species may contract at least minimally on all of the main Hawaiian Islands with a majority forecast to contract substantially (eight of 10 species). Except on Hawai`i Island, we projected net percent change for all 10 alien species to contract moderately to substantially, with many forecast to expand minimally. On Hawai`i Island, *Lantana camara* was projected to increase moderately by end-of-century while all other aliens contracted moderately to substantially. Within HAVO, we forecast net percent change for eight of the 10 alien species to contract substantially, *Schinus terebinthifolius* to contract minimally, and *Lantana camara* to expand substantially.

6.2. Patterns of Change in Species Range Relative to SEAs

For the most part, the net percent change in native species range was negative within the 37 SEAs. In 15 SEAs, native species ranges contracted substantially including the SEAs around the lower portion of Mauna Loa Strip and around Kīlauea Crater, areas that receive intense visitor pressures and also are important for cultural practitioners. In six SEAs, native species contractions were split among minimal, moderate and substantial categories. In 14 SEAs (12 occurring below 1,200 m elevation), native species contractions were split about evenly between minimal and substantial contractions. Two SEAs — East Rift and Puu Huluhulu — showed predominantly minimal contractions. We projected net percent change for most alien species to be negative in all 37 SEAs, except for *Lantana camara* and *Schinus terebinthifolius* which showed mixed results ranging from substantial contractions to substantial expansions in several SEAs.

Only two SEAs (East Rift and Koa) were projected to have an increase in native species richness, while one SEA (Kahuku Mauka) was expected to maintain its current species richness. A majority of the SEAs (24 of 37, or 65%) may lose more than half of the native species modeled here, while the remaining 10 SEAs could lose up to half their native diversity by the end-of-century. Thus, a majority of SEAs may not provide suitable habitat for even half of their current native species richness by the end-of-century. Twenty-nine SEAs were projected to lose more than half of their alien diversity, while five SEAs may lose up to half their alien species.

7. Analysis and Findings

At the present time, good congruence exists between native species richness and SEA locations (top panel Figure 1). Areas with a high number of native species, hotspots with ≥ 23 species, occurred in the Mauna Loa Southwest Rift, Mauna Loa Strip and East Rift tracts (where tracts are sections or portions of the park). Only one small SEA exists in the Mauna Loa Southwest Rift tract, whereas extensive SEAs currently occur in both the Mauna Loa Strip and East Rift tracts. The congruence, however, was projected to breakdown over time, and by the end-of-century many of the existing SEAs will remain in areas with suitable habitat for only a limited number of species (bottom panel Figure 1). Of particular interest were the forecasted remnant hotspots on the eastern edge of the Mauna Loa Southwest Rift tract, eastern portion of Olaa tract, and south and east areas of the East Rift SEA, as we projected these areas to remain relatively rich (≥ 19 overlapping native species).

8. Conclusions and Recommendations

Climate is a key determinant of species distribution. Geophysically explicit species range modeling offers a powerful option for evaluating plant species response to future climate conditions. Based on relationships of current climate conditions in which a species has been observed, models can be used to predict species responses to forecasted climates (Fortini et al. 2013). Forecasted species ranges may be used to focus management efforts on maintaining species where the climate is projected to threaten their existence, as well as to facilitate establishment of SEAs at HAVO in areas where species may be expected to shift.

Within HAVO, approximately two-thirds of the native species were projected to exhibit net range contraction (18 of 29), while about one-third (11 of 29) showed expansion. The species that showed the largest contractions typically have restricted bioclimate envelopes under current conditions. Because of the predominance of range contractions and limited range expansions, we projected a majority of the current SEAs will lose a majority of the native species we modeled, especially those SEAs occurring below 1,200 m. Net range expansion typically occurred for the limited number of species that colonize pioneer, young lava flows where sub-alpine and alpine environs were projected to become suitable habitat under future precipitation and temperature regimes, i.e., when bioclimatic envelop and climate change metrics matched. Within HAVO, the forecasted amount of range contraction exceeded expansion for all but one alien species (*Lantana camara*). These contractions were expected to occur in most SEAs, including SEAs at low, middle and high elevations.

9. Management Applications and Products

Forecasted shifts in suitable habitat for native plant species will assist park managers in assessing configuration of and prioritizing future work in SEAs. Potential changes to SEAs could include altering boundaries of existing SEAs, establishing new ones, or expanding existing SEAs to incorporate future diversity hotspots in areas not currently managed by park staff. There was good congruence between current (2000) native species richness and SEA configuration. However, under forecasted end-of-century climate projections where drier areas become drier, wetter areas become wetter, and temperatures increase everywhere, but more so at high elevations, our results suggest that substantial shifts in species range may occur across HAVO. As such, the congruence between species richness hotspots and SEAs diminished over time, so that by the end-of-century many projected species hotspots occurred outside of current SEA boundaries and in many cases outside HAVO.

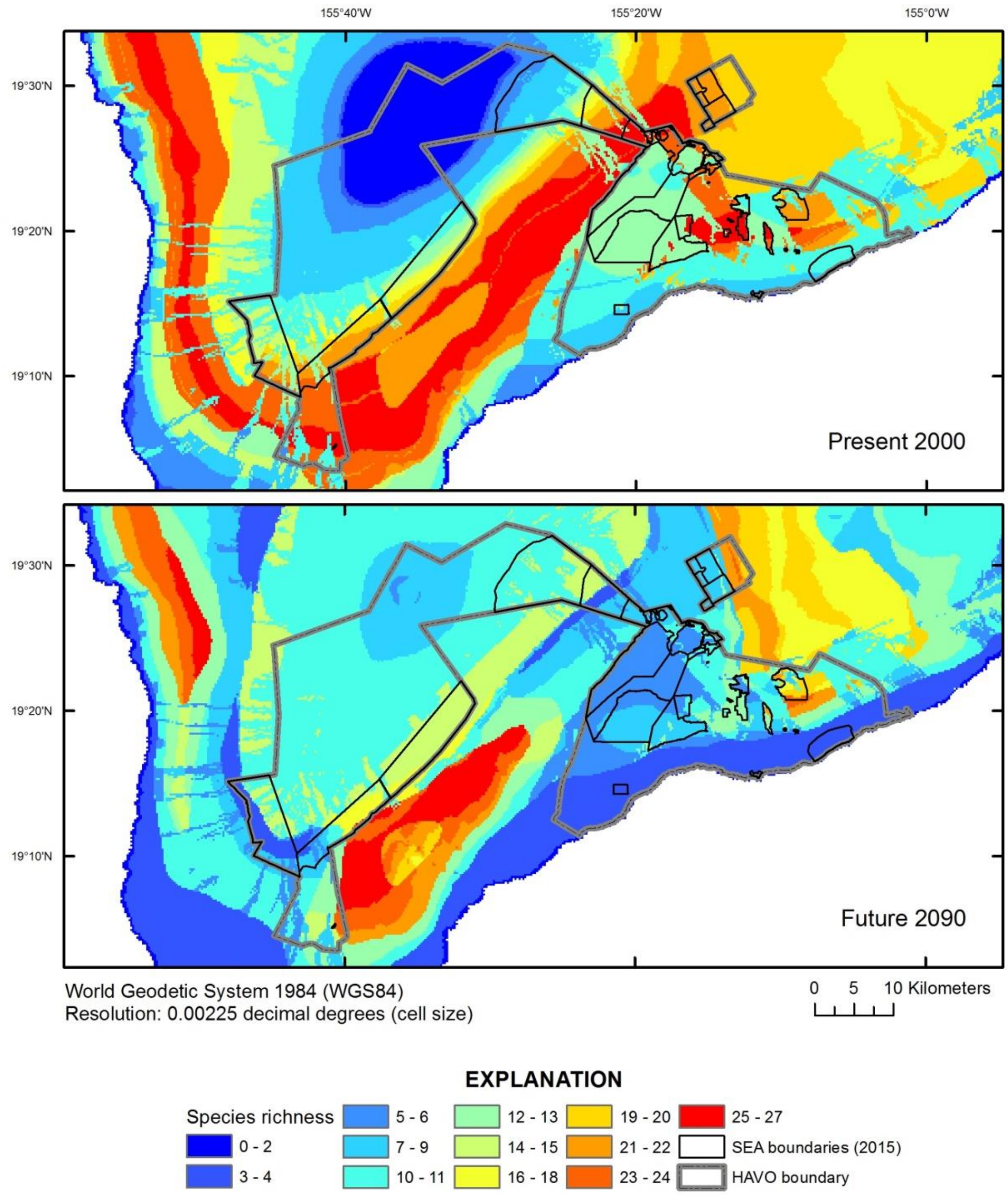

Figure 1. Native species richness using cool to warm colors to represent overlapping distributions of few to many species, respectively. The top panel shows that the present (year 2000) distribution of hot spots within HAVO align well with the distribution of SEAs. As shown in the lower panel, projected species richness at the end-of-century (year 2090) predominately recedes from HAVO, resulting in few species hotspots within SEA boundaries.

While current resource management actions (e.g., fencing and control of ungulates, invasive species control, outplanting restoration) will continue to be critical for conservation of plant species and communities, the rate of climate change is an additional factor that will affect habitat suitability. Assisted colonization, the translocation of organisms outside their historically documented range in anticipation of more suitable future conditions, may be a conservation option for consideration.

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A direct application of our projections is that they can be used to identify locations where major changes in habitat conditions are predicted and where plants are projected to respond to future conditions. Areas with high species turnover occur where climate change signal is strongest, indicative of areas projected to experience greatest climate change. Obtaining additional environmental data in these areas, for example deploying weather stations, will help managers understand what trajectory and extent climate change is occurring, while vegetation monitoring will provide information on how plants are responding to these measured changing conditions.

10. Outreach

The project team has presented the project methods and results at several venues where managers, researchers and decision-makers attended; thus, reaching out to key local and state management agencies. The results have been discussed at meetings with managers in the Cultural Resources and Natural Resources divisions of Hawaii Volcanoes National Park. The project results were also shared publically via a recorded webinar hosted by the PICSC. Future public outreach of this research includes the University of Hawaii at Hilo Climate Change Boot Camp in August, 2016, and the IUCN World Conservation Conference, Honolulu, in September, 2016. Finally, the team has submitted a detailed report of the project research to the USGS Science Publication Network to be published as an open access Scientific Investigation Report, which we expect to be available in 2016.

10.1. Presentations

Berkowitz, P., R. Camp, K. Brinck, J. Jacobi, R. Loh, J. Price, and L. Fortini. Impacts of projected climate change on select Hakalau plant species. *Hakalau Forest NWR Open House*, Hilo, HI, April 15, 2016.

Camp, R., P. Berkowitz, K. Brinck, J. Jacobi, R. Loh, J. Price, and L. Fortini. Potential impacts of climate change on vegetation management in Hawaii Volcanoes National Park. *Hawaii Ecosystems Meeting*, July 7-8, 2016, Hilo, HI, USA.

Camp, R. J., K. W. Brinck, P. Berkowitz, J. D. Jacobi, and R. Loh. Assess projected climate change effects on vegetation management strategies within Hawaii Volcanoes National Park. *Pacific Island Climate Science Center / PICCC Science Symposium*, February 26-27, 2015, Honolulu, HI, USA.

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Camp, R. J., K. W. Brinck, P. Berkowitz, J. D. Jacobi, and R. Loh. Assess projected climate change effects on vegetation management strategies within Hawaii Volcanoes National Park. *Graduate Student Seminar, University of Hawaii at Hilo*, September 3, 2015, Hilo, HI, USA.

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